# Fly Ash Separation Technology and its Potential Applications

**Yang Dong, Jinder Jow, Jianhui Su and Shih-Yaw Lai**

Performance Materials Center, National Institute of Clean-and-Low-Carbon Energy, P.O. Box 001 Shenhua NICE, Future Science & Technology City, Changping District, Beijing, China 102209

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ABSTRACT

Significant variations in the chemical and physical compositions of fly ash are recognized as critical issues for fly ash to be used in various applications.  The quality of fly ash depends not only on the coal types and sources (chemical composition), but also the power plant processing conditions and the collection system (physical composition). From materials science standpoints, three fundamental properties of fly ash are critical to its applications: chemical compositions, morphology, and particle size and its distribution. This paper gives briefly discussion on each fundamental property with special emphasis on the particle size and its distribution through fly ash separation and its impact on the applications.

Various separation process technologies are commercially available to increase the fly ash utilization value by producing finer particles as well as separating those with special properties, such as unburned carbon, cenosphere, magnetite, etc.  Finer fly ash has higher surface area, in general higher reactivity, thus resulting in higher value. Obviously, particle size is one of key criteria to classify fly ash. The typical size reference is 45 µm.  According to the Chinese standard GB1596-2005, Class I, II, and III fly ash are defined as no more than 12%, 25%, and 45% by weight, respectively, to this reference. However, the ultra-fine sizes (e.g. ≤5µm or submicron) are not included to truly reflect their value. This paper presents a unique dry separation technology established at National Institute of Clean-and-Low-Carbon Energy. This technology provides an option for the industry to produce the 1 – 3 µm fly ash products with consistent quality in terms of particle size distribution for high value applications (e.g. polymer fillers and coating applications) to maximize its utilization value, in addition to its general use in cement and concrete applications.

## INTRODUCITON

Fly ash is a fine powdery material produced by burning coal to generate electricity, primarily in pulverized coal combustion (PCC) boilers [1]. Huge amounts of ash and related by-products have been generated since the coal firing for power generation began in the 1920s. The annual production of fly ash was estimated around 1.5 billion tons worldwide and about 0.4 billion tons for China in 2010 [2]. Even though the fly ash utilization has reached about 40% globally and up to 68% in China [2], the disposal of the large amount of un-utilized fly ash is still a serious environmental problem. A substantial amount of ash is disposed in landfills and/or lagoons at a significant cost to the utility companies and thus to the consumers.

The Guohua Power Company, a subsidiary of Shenhua Group [3], has 21 coal-fired power plants as shown in Figure 1. The amount of fly ash each year produced from these plants is estimated about 5~6 million tons. Power plants located in the remote areas still have low fly ash utilization, and those near the coast regions or the metropolitan area do not obtain the maximum value of full fly ash utilization. How to fully utilize fly ash for plants located in the remote areas, maximize the utilization value for each power plant, and reduce its environmental impact are one of the critical programs at National Institute of Clean-and-Low Carbon Energy (NICE) [4], founded in 2009 by Shenhua Group.

Figure 1 location map of Guohua power plants

Significant variations in chemical and physical compositions have been recognized as critical issues for fly ash for various applications, particularly for those high value applications. Chemical compositions of fly ash depend on the coal types and sources. Below is the list of chemical compositions of fly ash from various coal types [5].

| Key compositions/coal types | Bituminous | Subbituminous | Lignite |
|---|---|---|---|
| $SiO_2$ (%) | 20-60 | 40-60 | 15-45 |
| $Al_2O_3$ (%) | 5-35 | 20-30 | 20-25 |
| CaO (%) | 1-12 | 5-30 | 15-40 |
| $Fe_2O_3$ (%) | 10-40 | 4-10 | 4-15 |
| LOI (%) | 0-15 | 0-3 | 0-5 |

Physical compositions, % glassy content and particle size and distribution, depend on the power plant processing conditions and the ash collection system. The glassy content can be > 90% for an IGCC (integrated gasification combined cycle) plant due to its highest combustion temperature of 1800°C, 77% - 90 for the most PCC (pulverized coal combustion) plants at the boiler temperature around 1200 – 1500°C, and 57 – 73% for the fluidized bed plant at the temperature of 850°C [6]. Fly ash from the coal-pulverized combustion process typically has 75 – 90% glassy content and 10 to 25% crystalline content, such as quartz, mullite, and magnetite.

Among these three basic properties, the particle size distribution is the most important property since it has the widest variation and range. It is also considered as one of the key parameters to classify fly ash. For example, the Chinese standard GB1596-2005 defines Class I, II, and III fly ash based on no more than 12%, 25%, and 45% by weight of fly ash greater than 45 µm (325 mesh), respectively. Of course, not all fly ash materials can meet these requirements. It is also well-known that finer fly ash has higher surface area, higher reactivity, thus resulting in higher value. Various dry separation process technologies are commercially available to separating fine particle size by screen mesh, cyclone, or milling. Generally, the lowest particle size is about 10 µm by the cyclone separation and 25 µm (500 mesh) by the mesh method. The milling requires significant energy to grind down to 1-3 µm or submicron sizes. Consistently producing the finer sizes, particularly ⩽5µm ($D_{50}$), is not widely available by a dry separation method, except one wet method patented by US 6533848. This wet method can produce fly ash with a mean particle size range of 2-4 µm ($D_{50}$) comprising fly ash slurry in the presence of a super-plasticizer.

This paper presents a unique dry separation technology established at National Institute of Clean-and-Low-Carbon Energy, Beijing, China, to produce 1 – 3 µm fly ash at a very low energy cost. This separation process is capable of producing at least 3 products with consistent quality in terms of particle size and distribution. For example, product 1 with $D_{50}$ < 1 µm can be sold at the high value used for nano-composites. Product 2 with $D_{50}$ between 1 and 3 µm can be used as fillers for polymer and coating applications. Product 3 can still meet Class I or II fly ash used for cement or concrete applications.

## ADJUSTABLE DRY FLY ASH SEPARATION TECHNOLOGY

Our separation process system consists of a feeder, an air blower, a centrifugal separator with an adjustable fan speed, a cyclone separator, a filter bag, and an induced draft fan as shown in Figure 2.

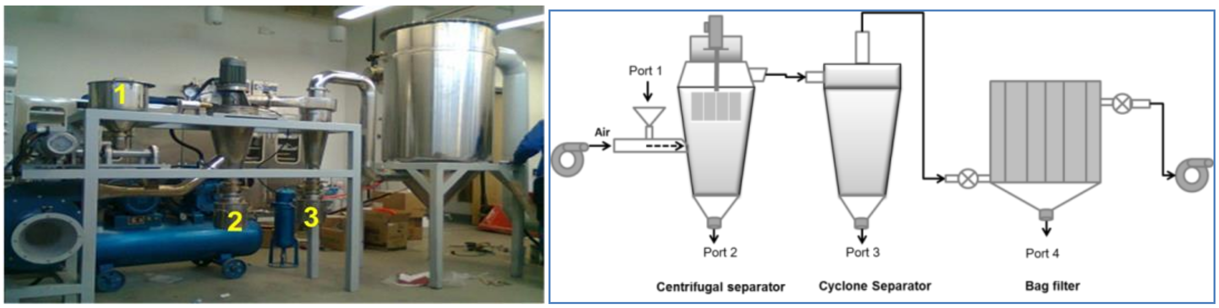


Figure 2 Photo and schematic diagram of the fly ash separation system at NICE

The separation capacity of this lab scale process is about 20 kg/hour. The speed of the centrifugal fan is in a tunable range from 200 to 3,000 rpm. The diameter is about 0.3 m for the centrifugal separator and 0.2 m for the cyclone separator. The air flow for the whole system is in the range of 500-1,400 $m^3$/h.

## EXPERIMENTAL

### Materials

Fly ash materials were obtained from six Guohua power plants, identified as #1, #2, #3, #4, #5, and #6 power plants. The power plant #3 and #4 provided two samples with two different particle sizes, identified as #3 fine and #3 coarse, and #4 fine and #4 coarse, respectively. The power plant #5 also provided additional 5 fly ash materials collected from each of 4 different electrostatic ports, identified as #5-1, #5-2, #5-3, and #5-4, respectively, and one mixture from electrostatic ports, identified as #5 mix.

### Measurements

**Chemical compositions**: Chemical compositions of the fly ash materials from 6 power plants were measured by the XRF method (Rigaku Fully Automated Sequential X-ray Spectrometer, Model: ZSX Primus Ⅱ) at NICE. The sample tablet was prepared by compressing at high pressure (25Mpa) for 60s. The results are listed in Table 1. All these fly ash materials have two major components, $SiO_2$ (33 – 54%) and $Al_2O_3$ (18 – 56%), minor components of $Fe_2O_3$ (2 – 7%), CaO (1 – 13%), $K_2O$ (0.4 – 3.8%), $SO_3$ (0.8 – 1.8%), MgO (0.3 – 1.7%), and $Na_2O$ (0 – 1.1%), and trace amount (< 0.1%) of heavy metals, such as Cr, Cd, Pb, etc. No Hg was detected in these samples. Among these 6 samples, samples #1, #2, and #5 are Class C due to the CaO content > 10%, while the rest are Class F. The sample #6 has extremely high $Al_2O_3$ content up to 55.66% suitable for the Al extraction. All fly ash materials have LOI less than 3%.

Table 1 chemical compositions of the fly ash from six Guohua power plants

| | #1 | #2 | #3 | #4 | #5 | #6 |
|---|---|---|---|---|---|---|
| $SiO_2$ | 41.25 | 45.07 | 50.07 | 50.54 | 53.27 | 33.92 |
| $Al_2O_3$ | 35.58 | 30.04 | 28.29 | 27.57 | 18.11 | 55.66 |
| $Fe_2O_3$ | 5.94 | 6.54 | 5.63 | 6.98 | 5.52 | 2.16 |
| CaO | 10.14 | 10.50 | 7.91 | 7.72 | 12.86 | 1.02 |
| MgO | 0.68 | 1.67 | 1.37 | 1.10 | 1.20 | 0.32 |
| $K_2O$ | 1.25 | 1.68 | 1.90 | 2.09 | 3.77 | 0.45 |
| $Na_2O$ | 0.84 | 0.72 | 1.10 | 0.71 | 1.09 | 0.00 |
| $SO_3$ | 1.73 | 1.09 | 0.99 | 0.86 | 1.04 | 1.58 |
| $Cr_2O_3$ | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | - |
| CdO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | - |
| PbO | 0.02 | 0.02 | 0.02 | 0.03 | 0.01 | - |
| Hg | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | - |

**Particle size distribution**: The particle size distributions of all fly ash samples were measured by a laser particle size analyzer (Malvern mastersizer 2000) and using water as a dispersant.

## RESULTS AND DISCUSSIONS

### Wide variation in particle size distributions from different plants

Eight fly ash samples from 6 different Guohua power plants were compared in terms of particle size distribution. Figure 3 shows the significant variations in their particle size distributions. The results of their ranges, $D_{50}$, and GB1596 classifications are listed in Table 2. Apparently, not all fly ash samples can meet Class I or II.

Table 2 Range, $D_{50}$, and Classifications of 8 fly ash samples

| Sample ID | Range (um) | $D_{50}$ (um) | > 45 um | Class |
|---|---|---|---|---|
| #1 | 0.24 - 505 | 14.5 | 18% | II |
| #2 | 0.24 - 505 | 13.0 | 17% | II |
| #3 coarse | 3.90 - 570 | 105.0 | 89% | NR |
| #3 fine | 0.27 - 90 | 2.9 | 2% | I |
| #4 fine | 0.27 - 505 | 13.5 | 22% | II |
| #4 coarse | 0.27 - 505 | 65.0 | 60% | NR |
| #5 | 0.27 - 400 | 7.5 | 18% | II |
| #6 | 0.24 - 80 | 3.7 | 1% | I |

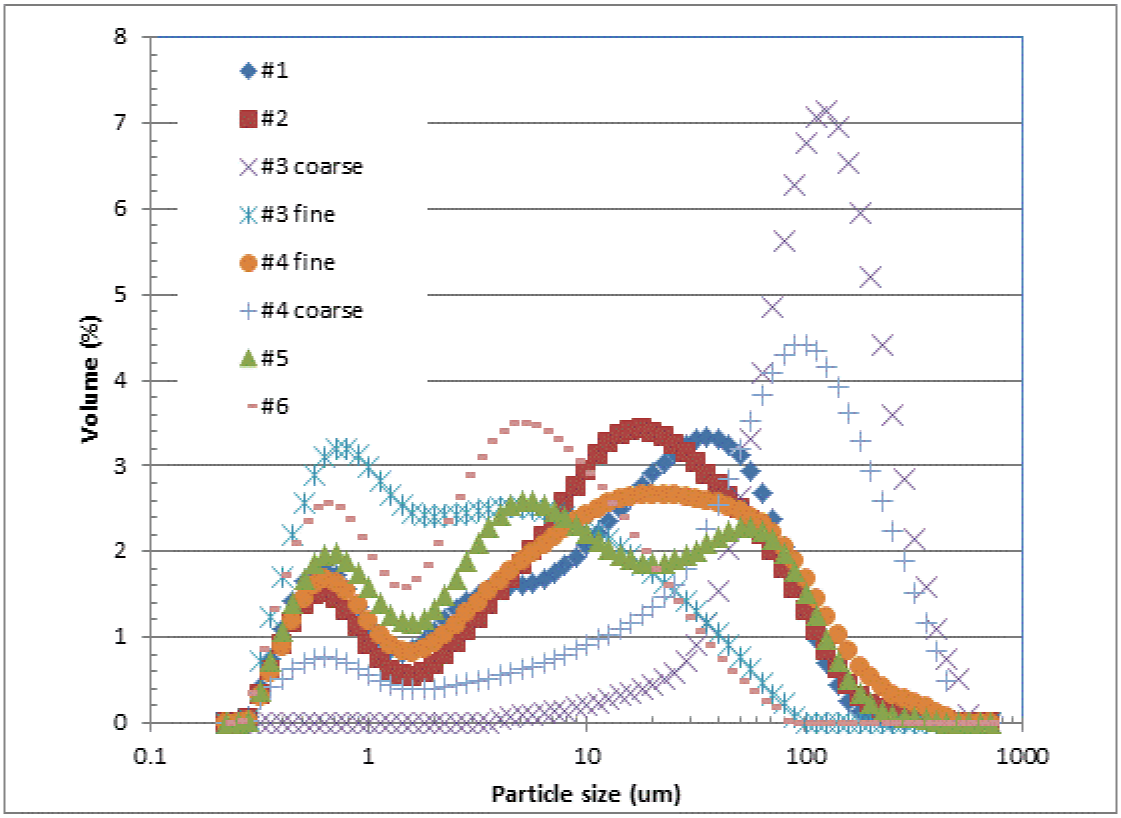

Figure 3 Particle size distributions of 8 fly ash samples from Guohua power plants

**Different $D_{50}$ but same particle size range from electrostatic ports:**

Conventional belief states that each power plant can collect finer fly ash particle size and distribution at the further electrostatic port and the fly ash product with finer particle size will have the maximum particle size smaller than the fly ash product with the coarse particle size. Five fly ash samples from the power plant #5 including four samples from each of 4 electrostatic ports and the mixture were used to validate this conventional belief. The particle size distributions of these 5 fly ash samples are shown in Figure 4. The results show that all samples have a similar particle size range, regardless of the differences in $D_{50}$ as listed in Table 3. These results do not support the conventional brief for lower particle size with the range having a lower maximum particle size. In addition, two fly ash samples from the power plant #4 listed in Table 2 also show different particle size, $D_{50}$, but can still have the same particle size range.

Table 3. $D_{50}$ and Range of Jinjie fly ash samples

| Sample ID | $D_{50}$ (um) | Range (um) |
|---|---|---|
| #5 Mix | 8.9 | 0.25 - 326 |
| #5-1 | 13.0 | 0.25 - 400 |
| #5-2 | 5.0 | 0.25 - 260 |
| #5-3 | 8.0 | 0.25 - 360 |
| #5-4 | 5.6 | 0.25 - 230 |

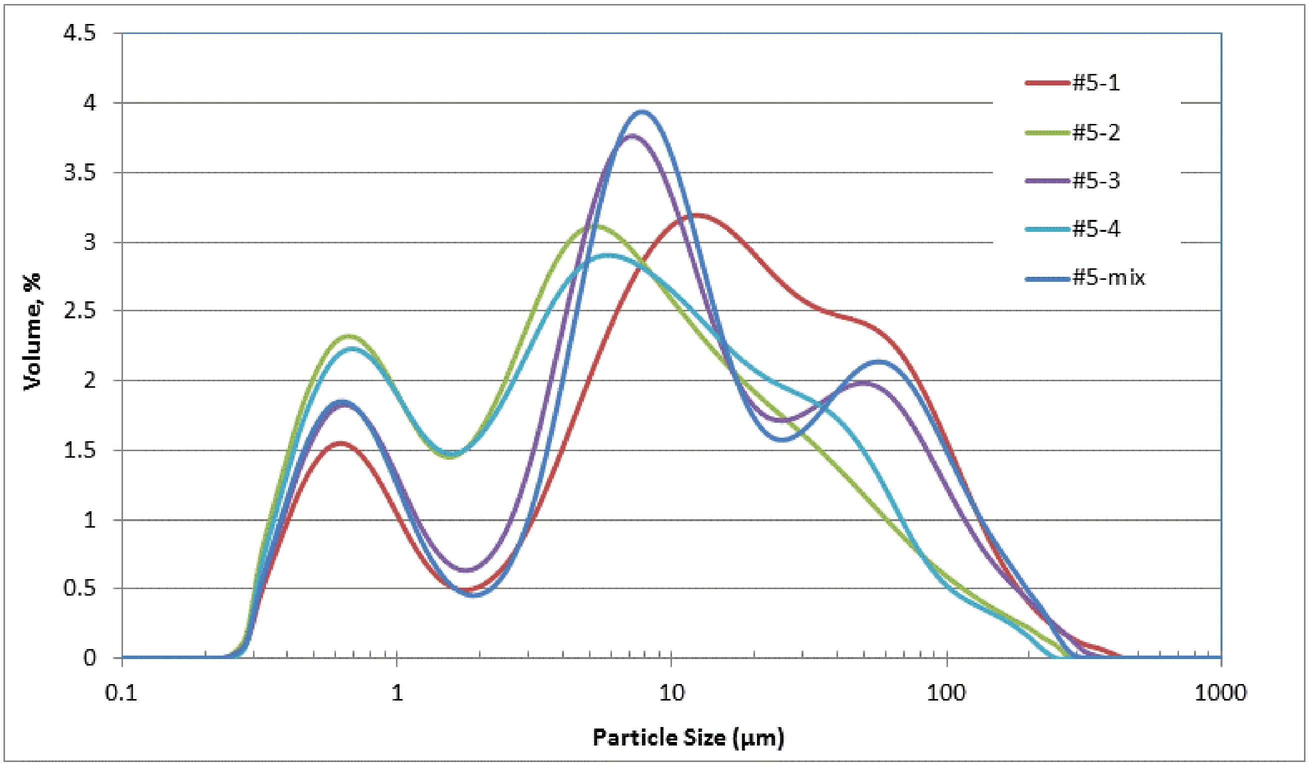

Figure 4. Particle size distributions of 5 fly ash samples from the power plant #5

**Different separated fly ash products at different centrifugal speeds**

Fly ash samples from the power plant #1 were run at different centrifugal speeds of 2900, 2000, 1000, and 500 rpm, respectively, while the air flow was kept at about 1000 $m^3$/h. The separation results are summarized in Table 4 and also shown in Figure 5.

The particle size and the amount of separated fine fly ash (from Port 3) decrease from 13.6 to 2.3 µm with increasing the centrifugal speed. The particle size of separated coarse fly ash from centrifugal part (from Port 2) also decreases from 75.8 to 29.7µm but the amount increases with increasing the centrifugal speed. The results were also confirmed by SEM analysis as shown in Figure 5 (on the right). The separated fine particle size at the centrifugal speed from 2,000 to 3,000 rpm can achieve $D_{50}$ less than 5 µm which are suitable to be used as fillers for polymer composites as listed in Table 4.

Table 4 Summary of fly ash particle size at different separation speeds

| Max. exhaust, Inhaust at No 4 | 1# (BJ FA) | 2# (Coarse part) | | | 3# (fine part) | | |
|---|---|---|---|---|---|---|---|
| | kg | kg | ratio | D50 | kg | ratio | D50 |
| 2900 rpm | 5 | 3.6 | 72% | 29.7um | 0.7 | 14% | 2.3um |
| 2000 rpm | 5.5 | 3.7 | 67% | 37.8um | 1.3 | 24% | 3.3um |
| 1000 rpm | 5.3 | 2.2 | 42% | 55.5um | 2.7 | 51% | 8.2um |
| 500 rpm | 5 | 0.86 | 17% | 75.8um | 4.1 | 82% | 13.6um |

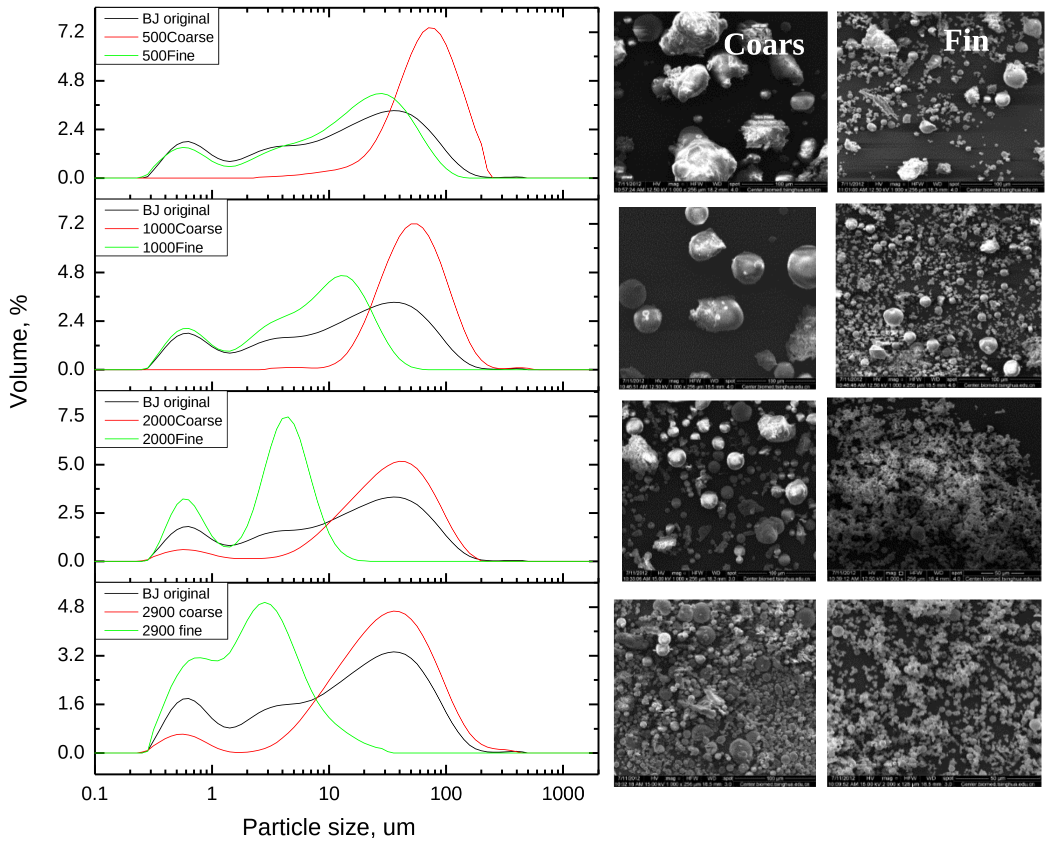


Figure 5 Particle size and distribution of separated fly ash at different centrifugal speed and corresponding SEM analysis

## Chemical compositions of separated fly ash products

There is a question whether chemical compositions will be changed after separation. The chemical compositions of the original and two separated fly ash samples run at 2900 rpm were analyzed by using the XRF method as shown in Figure 6. Figure 6 shows that the original and separated coarse and fine fly ash samples have the similar concentrations of $SiO_2$, $Al_2O_3$, $Fe_2O_3$, CaO, MgO, $K_2O$, and NaO etc. It concludes that separation does not alter the chemical compositions. However, the separated coarse fly ash sample is slightly darker than the original and fine fly ash sample with LOI increase less than 1 unit listed below.

| Fly ash sample ID | LOI | | | Average | std dev. |
|---|---|---|---|---|---|
| BJ (#1) original | 1.6% | 1.8% | 1.5% | 1.7% | 0.2% |
| BJ 2900 coarse | 2.3% | 2.1% | 1.9% | 2.1% | 0.2% |

| BJ FA | original | 2900 coarse | 2900ultrafine |
|---|---|---|---|
| $SiO_2$ | 41.2499 | 39.157 | 37.7192 |
| $Al_2O_3$ | 35.5755 | 37.8758 | 35.6145 |
| CaO | 10.1399 | 11.6979 | 11.0384 |
| $Fe_2O_3$ | 5.9361 | 5.8034 | 6.9982 |
| $SO_3$ | 1.7349 | 1.34 | 2.7213 |
| $TiO_2$ | 1.6121 | 1.4479 | 1.6428 |
| $K_2O$ | 1.2465 | 0.7431 | 0.9983 |
| $Na_2O$ | 0.8434 | 0.9007 | 1.2754 |
| MgO | 0.6837 | 0.4262 | 0.76 |
| $P_2O_5$ | 0.3067 | 0.1399 | 0.3935 |
| SrO | 0.2492 | 0.1665 | 0.2473 |
| MnO | 0.1423 | 0.1719 | 0.2172 |
| $ZrO_2$ | 0.0859 | 0.0456 | 0.0607 |
| BaO | 0.0806 | | 0.089 |
| PbO | 0.0194 | 0.0086 | 0.0361 |
| $Y_2O_3$ | | 0.0193 | 0.0198 |
| $Cr_2O_3$ | 0.0158 | 0.0099 | 0.0179 |
| ZnO | 0.0148 | 0.0072 | 0.028 |
| CuO | 0.0126 | 0.0063 | 0.0139 |
| NiO | 0.0119 | 0.0092 | 0.0152 |
| $Ga_2O_3$ | 0.0119 | 0.0063 | 0.0213 |
| $Nb_2O_5$ | 0.0062 | | |
| $Rb_2O$ | 0.0059 | 0.0031 | 0.0034 |
| $Co_2O_3$ | 0.0054 | 0.0044 | 0.0102 |
| $CeO_2$ | | | 0.0467 |
| $ThO_2$ | 0.0045 | 0.0031 | 0.005 |
| $GeO_2$ | 0.0026 | | 0.003 |
| $SeO_2$ | 0.0025 | 0.0015 | 0.0034 |

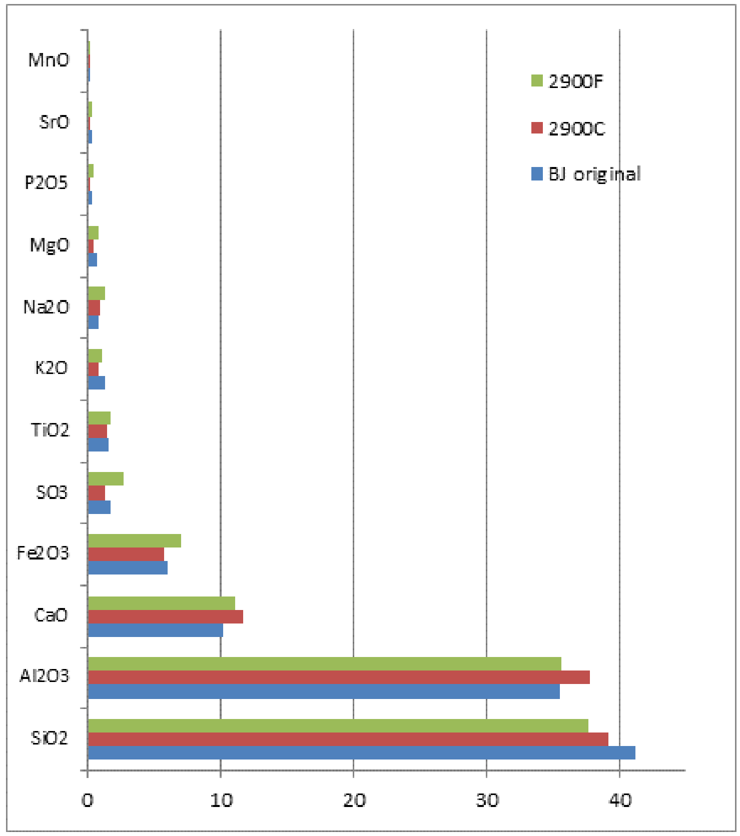


Figure 6 chemical composition of separated fly ash

**Consistent product quality from various fly ash sources:**

Three fly ash materials from three different power plants, #1, #3, and #5 were used in this study. The original particle size distributions are shown in Figure 7. All three samples were run at 2900 rpm to produce the portions with finer and coarser particle sizes. The results are listed in Table 5. It clearly shows different fly ash materials with different particle size distribution can be extracted by our process to produce the consistent product quality with $D_{50}$ in the range of 1 to 3 μm as shown in Figure 8.

Table 5. $D_{50}$ of the original and separated fly ash products at 2900 rpm

| Sample ID (original and after 2900 rpm) | Original $D_{50}$ (μm) | Coarse $D_{50}$ (μm) | Ultrafine $D_{50}$ (μm) |
|---|---|---|---|
| #1 | 14.5 | 27.0 | 2.1 |
| #3 fine | 2.9 | 6.6 | 1.6 |
| #5 | 7.5 | 16.0 | 2.1 |

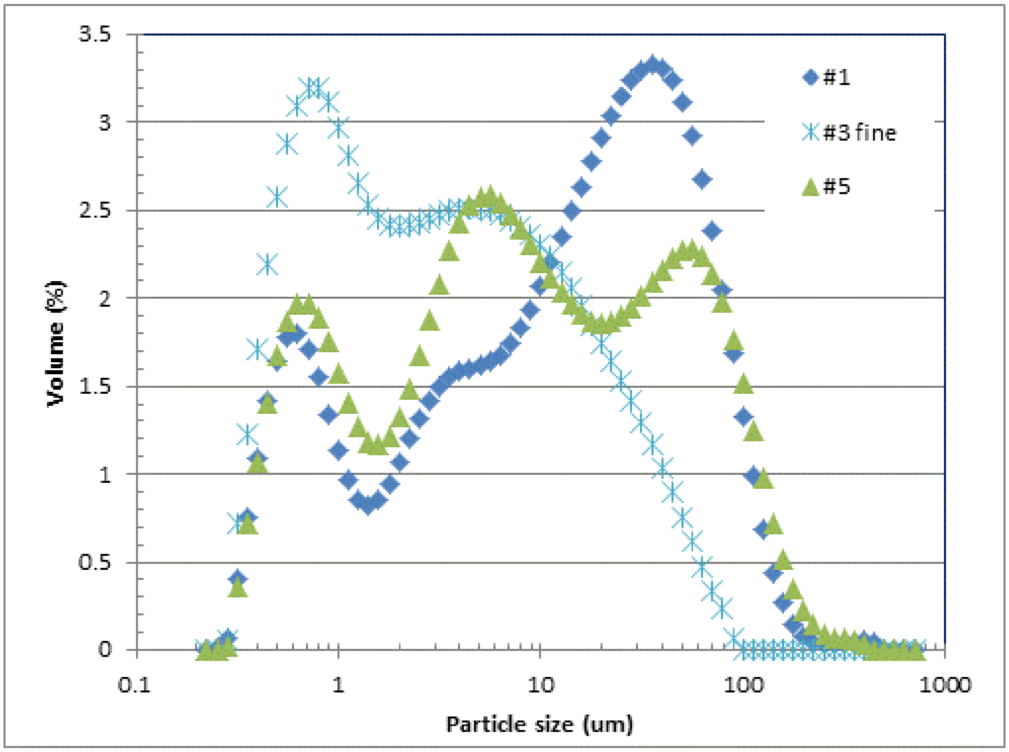

Figure 7. Particle size distributions of three different fly ash samples

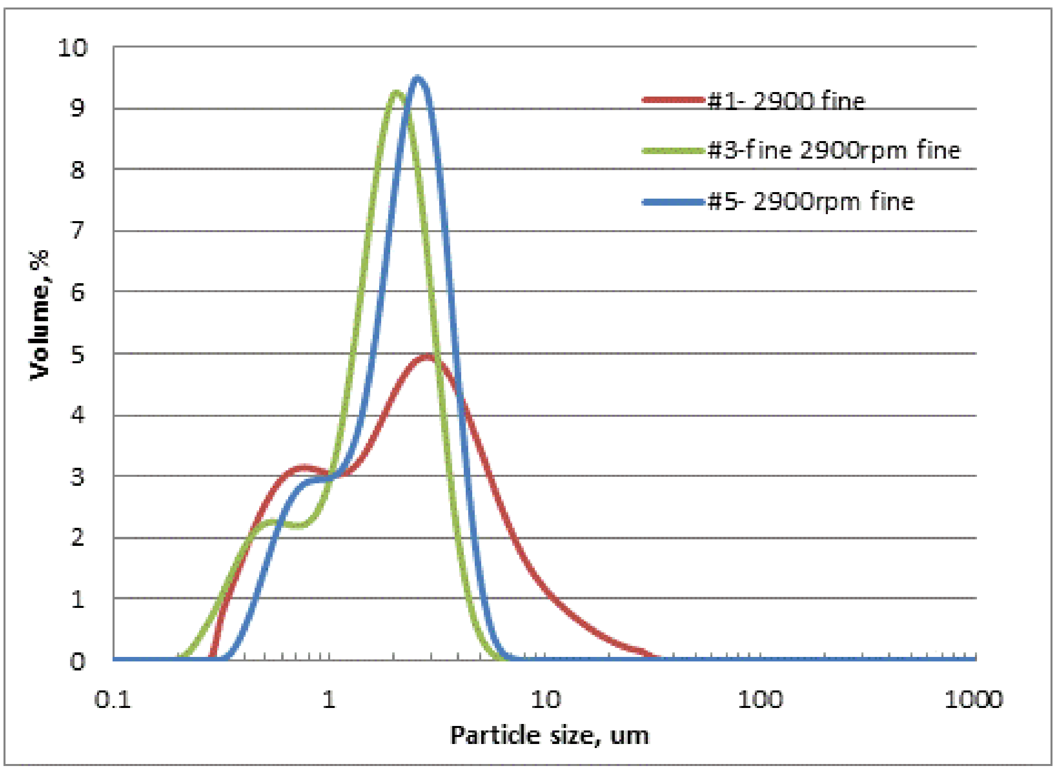


Figure 8. Consistent product quality

## CONCLUSIONS

Fly ash materials from 6 different Guohua power plants show the wide variations in chemical compositions as well as particle size distributions. Our adjustable dry separation technology demonstrates the capability of producing the consistent product quality of 1 – 3 µm fly ash products suitable for high value applications, such as fillers for polymers and coating applications.

A few key discoveries from this study are also summarized below:

- Collecting different fly ash materials from different electrostatic port have different $D_{50}$ but can still have the same particle size range.

- Consistent 1 – 3 µm fly ash product quality in terms of particle size and distribution can be obtained, regardless of the wide particle size distributions from different power plants.

- Separated fly ash products do not have significant differences in chemical compositions as compared with the original fly ash material.

- Higher centrifugal speed produces finer fly ash product, lower $D_{50,}$ with less weight % from the total weight of the fly ash sample.

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